

Thorium abundances on the lunar surface

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Abstract. Measurements of absolute thorium abundances on the lunar surface are presented using both the high- and low-altitude data taken with the Lunar Prospector Gamma-Ray Spectrometer. An analysis of the uncertainties shows that the measured uncertainties are less than 0.5 $\mu\text{g/g}$ and are close to the theoretical limit of Poisson statistics. Currently, the overall systematic uncertainties are likely dominated by variations in background counts. The relative systematic uncertainties are thought to be no larger than 30% for the high-altitude data and 15% for the low-altitude data. A comparison of high- and low-altitude data show that most regions having thorium abundances greater than 6 $\mu\text{g/g}$ are likely small area regions less than or equal to (150 km)². Using lunar topographic data, we have shown that the thorium abundances in the lunar highlands and portions of South-Pole Aitken (SPA) basin are larger for lower elevations. We have also studied a number of regions with anomalously high thorium abundances such as the northwestern region of SPA basin, the crater Arago in western Tranquillitatis, and the Compton/Belkovich region in the northeastern highlands, as well as the Tycho crater which has very low thorium abundances. In particular, the Compton/Belkovich region appears to be enriched with evolved rocks such as alkali anorthosite and currently represents the only such extended region on the Moon that has been identified.

1. Introduction

Thorium is a key element for tracing the history and evolution of the Moon and the lunar surface because it is enriched in a material called KREEP [(K) potassium, (REE) rare-earth elements, (P) phosphorus] which is thought to have formed between the lunar crust and mantle. Specifically, it is thought that as the Moon cooled and minerals crystallized from a magma ocean, dense minerals sank to form the mantle and light minerals floated to the surface to form the crust. The last material to crystallize was rich in elements (e.g. Th, K, and REE) that do not substitute easily into the crystal lattice of the major rock forming minerals. Detailed explanations of how KREEP relates to lunar formation and evolution can be found in many references and are therefore not discussed here [e.g. *Vaniman et al.*, 1991, *Warren and Wasson*, 1979, *Warren*, 1985 and references therein]. In this paper, we present and describe the most recent thorium abundance data obtained with the Lunar Prospector (LP) Gamma-Ray Spectrometer (GRS). A rigorous determination of the absolute thorium abundance from LP GRS data requires that detailed detector modeling and spectral fitting analyses be carried out. However, because the 2.61MeV γ -ray line produced by ^{232}Th is very strong, has few competing γ -ray lines in its energy range, and shows large variations over the lunar surface, it is possible to obtain estimates of relative and absolute thorium abundances by simply measuring γ -ray counting rates within an energy window surrounding the 2.61MeV line. Preliminary results of this window counting rate technique are described in *Lawrence et al.* [1998, 1999a]. A number of key results have been discovered regarding the abundance of thorium on the lunar surface using this technique. These results include the following:

1. The highest thorium abundances on the Moon (8 – 10 $\mu\text{g/g}$) are located around the Imbrium basin region. These high-thorium regions are associated with craters and highlands regions, some of which may be related to Imbrium ejecta and/or post-Imbrium KREEP volcanism. In particular, the regions with the highest thorium abundances are near Aristillus crater, Aristarchus crater, Mairan crater, Kepler crater, the Fra Mauro region near the Apollo 14 landing site, the Apennine bench region near the Apollo 15 landing site, and the highlands regions north and northwest of Imbrium basin.

2. The mare basalt within Imbrium basin has distinctly lower thorium abundances ($2 - 5 \mu\text{g/g}$) than many of the surrounding regions, but has higher thorium abundances than the eastern mare basalt regions ($1 - 3 \mu\text{g/g}$);
3. South Pole-Aitken (SPA) basin has moderately high thorium abundances ($2 - 5 \mu\text{g/g}$) compared to the surrounding highlands ($< 2 \mu\text{g/g}$). In addition, the locations within SPA having the highest thorium abundances do not appear to be areas with extensive mare basalt in contrast to the expectation of *Hawke and Spudis*, [1980].
4. There exists a moderately high thorium region ($2 - 4 \mu\text{g/g}$) in the lunar highlands (60°N , 100°E) which has a small spatial size ($150 - 300 \text{ km}$ diameter). While high in thorium compared to the surrounding highlands ($< 2 \mu\text{g/g}$), this region does not have any other abundance anomalies as determined by the Clementine spectral reflectance (CSR) measurements of *Lucey et al.* [2000].
5. The measured distribution thorium abundances closely matches the distribution of samarium and gadolinium abundances inferred from combined LP neutron spectrometer and CSR data [*Elphic et al.*, 1998, 2000].

Here, we expand on the previous studies by describing the absolute thorium abundance measurements in more detail. Specifically, thorium abundance measurements have been made from both high- and low-altitude data. Since the LP GRS is an uncollimated, omnidirectional γ -ray detector, the measured surface resolution is a direct function of the spacecraft height above the lunar surface. The surface resolution (full-width, half maximum) of the low-altitude data (mean spacecraft height: 32 km , see Table 1) is $\sim(45 \text{ km})^2$, which is three times smaller than the surface resolution of the high-altitude data (mean spacecraft height: 100 km) of $\sim(150 \text{ km})^2$. See *Reedy et al.*, [1973] for a general discussion of the surface resolution that can be obtained with planetary gamma-ray spectroscopy. In the initial study of *Lawrence et al.*, [1998], we presented relative thorium abundances using the high-altitude data on $5^\circ \times 5^\circ$ ($150 \text{ km} \times 150 \text{ km}$) equal area pixels. The first whole Moon measurements of absolute thorium abundances were presented in *Lawrence et al.*, [1999a] using the low-altitude thorium data on $2^\circ \times 2^\circ$ ($60 \text{ km} \times 60 \text{ km}$) equal area pixels. Here, we present together both high- and low-altitude

measurements of absolute thorium abundances measured on 60 km x 60 km equal area pixels. Note that while the high-altitude data in this paper are presented on 60 km x 60 km pixels, the surface resolution of the high-altitude measurements is still approximately $(150 \text{ km})^2$. We describe in detail the abundance uncertainties associated with the window counting rate method of calculating absolute abundances. Next, we discuss the global thorium data and examine the similarities and differences between the high- and low-altitude data. We then examine relationships between the global thorium data and other global data sets. Finally, we describe thorium abundances for a number of interesting locations on the Moon using the low-altitude thorium data.

2. LP GRS Data Sets

The LP thorium data are divided into two major data sets. A summary of the data sets is given in Table 1. A set of high-altitude data (mean spacecraft height: 100 km) was measured from 16 January, 1998 to 19 December, 1998 and a set of low-altitude data (mean spacecraft height: 32 km) was measured from 19 December, 1998 to 31 July, 1999. On October 6 – 8, 1998, the spin axis of the LP spacecraft was flipped from pointing towards the ecliptic north to the ecliptic south. Since the response of the GRS is asymmetric with respect to lunar latitude and spacecraft spin axis orientation [Lawrence *et al.*, 1998, Feldman *et al.*, 1999], the high-altitude data were sub-divided into two data sets corresponding to the two different spin axis orientations. After proper corrections are made, the two high-altitude data sets were combined into the single set of high-altitude data shown in Table 1.

GRS spectra were collected in time increments of 32-seconds during which time the spacecraft covered a ground track distance of roughly 50 km. To create a composition map, each spectrum is assigned to one of 11,306 approximately equal area (60 km x 60 km) pixels based on the instantaneous position of the spacecraft halfway through each data collection cycle. Currently, no corrections have been made to account for spacecraft motion during the data collection cycle. Table 1 shows the total number of 32-second spectra collected for each data set. Out of a possible 562 days of data collection, 13.7% (high-altitude) and 13.1% (low-altitude) of the data have been lost or is unusable for elemental mapping. Sources of loss include incomplete Deep Space

Network coverage, bad data sync words and/or check sums, spacecraft maneuvers, and solar energetic particle events, which saturate the GRS detector with very high background counting rates. The average number of measured spectra per $(60 \text{ km})^2$ pixel is also listed in Table 1 for the latitudes $\pm 90^\circ$, $\pm 45^\circ$, and 0° . Because LP is in a polar orbit, there are over 30 times more spectra collected per unit area at the poles than at the equator.

As explained elsewhere [Lawrence *et al.*, 1998, 1999a, b], various time dependent corrections have been made to the raw GRS counting rate data. These include corrections for gain variations in the GRS detector, dead time counting rate variations, counting rate variations due to the changing flux of galactic cosmic rays hitting the Moon, and variations in the solid angle subtended by the Moon due to the varying heights of the LP spacecraft. As part of the solid angle corrections, both the high- and low-altitude data sets were normalized to a spacecraft altitude of 100 km to enable easy comparisons between the data sets. Finally, corrections have also been made for variations due to the asymmetric response of the GRS for different latitudes.

3. Uncertainties in the Measured Thorium Abundances

Thorium abundances are derived by measuring the counting rate of the 2.61 MeV γ -ray line produced by radioactive decay of ^{232}Th . Because of the reasons listed in the introduction, estimates of absolute thorium abundances can be made by making the following assumptions: 1) Assume that the continuum background counts and non-thorium discrete line γ -ray counts within the 2.5 – 2.7 MeV window are constant over the Moon; 2) Define the pixel with the minimum window counting rate to have a thorium abundance of 0 $\mu\text{g/g}$. Assumption (2) does not probably hold in a strict sense because the lowest thorium abundances on the Moon are likely around $0.4 \pm 0.2 \mu\text{g/g}$ as measured from lunar highlands meteorites [Korotev, 1999]. However, since 0.4 $\mu\text{g/g}$ is comparable to some of the measured and/or estimated uncertainties (see below), to a first approximation, it is reasonable to use assumption (2). The minimum and maximum counting rates for the 2.5 – 2.7 MeV window are 115 and 194 counts per 32 seconds (high-altitude data set) and 91 and 185 counts per 32 seconds (low-altitude data set).

With the above assumptions, absolute thorium abundances are estimated from the GRS counting rate data using the following relation [Lawrence *et al.*, 1999a]:

$$C_{Th} = A_{Th}at\varepsilon F_{\gamma}. \quad (1)$$

Here, C_{Th} is the mean number of counts per 32 seconds above background within an energy band (2.5 – 2.7 MeV) around the 2.61 MeV full energy peak, A_{Th} is the weight fraction abundance of thorium in $\mu\text{g/g}$, a is the effective GRS detector area (54 cm^2 , see Feldman *et al.* [1999]), t is the collection time for a single spectral measurement (32 seconds), ε is the model-derived GRS detector efficiency at 2.61 MeV within the 2.5 – 2.7 MeV window, and F_{γ} is the expected flux of thorium γ -rays at the spacecraft per $\mu\text{g/g}$ of thorium on the lunar surface. In Lawrence *et al.* [1999a], the γ -ray efficiency was calculated to be 0.322 counts per incident γ -ray and the flux F_{γ} was calculated to be $0.0164 \text{ } \gamma \text{ s}^{-1} \text{ cm}^{-2} (\mu\text{g/g})^{-1}$ at a spacecraft height of 100 km. Estimates of absolute thorium abundances using equation (1) have been given in Lawrence *et al.* [1999a] for the low-altitude data. Here we describe in detail the uncertainties of these thorium abundance measurements. Specifically, uncertainties may result from counting statistics (Poisson statistics), imperfect time-dependent corrections, and a breakdown of the two assumptions just given. In the following sections, the uncertainties due to Poisson statistics, time-dependent corrections, and non-uniform background variations [a breakdown of assumption (1)] are investigated. While we expect the uncertainties due to assumption (2) are $<0.5 \text{ } \mu\text{g/g}$ [Lawrence *et al.*, 1999a], a detailed knowledge of the origin of the absolute background counts is needed before this assumption can be tested.

3.1 Statistical and data correction uncertainties

To estimate how much effect the time-dependent corrections (gain drifts, galactic cosmic ray variations, dead time corrections, etc.) have on the overall uncertainties, we can compare the measured variance of counts within individual spatial pixels with the uncertainties we would expect from Poisson statistics (counting time and photon statistics). Uncertainties due to Poisson statistics are the lower limit of the uncertainties

that can be obtained with GRS measurements. The abundance uncertainty for a given 60 km x 60 km pixel due to Poisson statistics is:

$$\sigma_{\text{Poisson}} = \frac{1}{a\epsilon t F_{\gamma}} \sqrt{\frac{C_{Th}}{N}}, \quad (2)$$

where N is the number of 32-second spectra measured in the pixel, $a\epsilon t F_{\gamma} = 9.12$ is the conversion factor from equation (1), and again C_{Th} is the mean number of counts measured per 32-seconds in each pixel. The measured abundance uncertainty in each pixel is:

$$\sigma_{\text{measured}} = \frac{1}{a\epsilon t F_{\gamma}} \sqrt{\frac{\sum_{i=1}^N (C_{Th,i} - C_{Th})^2}{N-1}}, \quad (3)$$

where $C_{Th,i}$ is the measured counts in a given 32 second spectrum i . σ_{measured} contains uncertainties due to Poisson statistics as well as systematic uncertainties such as imperfect time-dependent corrections.

Figure 1 shows scatter plots of the Poisson uncertainties (equation 2) versus the measured uncertainties (equation 3) for both uncorrected (black circles) and corrected data (gray crosses) for the high- and low-altitude data sets. If Poisson statistics were the only source of uncertainties, then all the data points would lie along the unity line. However, in both data sets, most of the uncorrected data fall above the unity line indicating that there are significant uncertainties not due to Poisson statistics. On the other hand, much of the corrected data cluster around the unity line indicating that most of the non-Poisson uncertainties have been removed.

There are some differences between the high- and low-altitude data. The corrected high-altitude data still lie somewhat above the unity line while the low-altitude data follow the line directly. This is not surprising as the high-altitude data cover over twice as much time as the low-altitude data (Table 1). This longer time span for the high-altitude data both reduces the Poisson uncertainties and increases the chance of applying

imperfect time dependent corrections. In addition, there was significantly more solar activity during the high-altitude portion of the mission than during the low-altitude portion of the mission. The increased solar activity likely increased the observed uncertainties for the high-altitude data. Nevertheless, it is clear from Figure 1 that the time dependent corrections are being carried out with sufficient accuracy so that uncertainties from Poisson statistics are the dominant source of measured uncertainties. Figure 2 shows the measured uncertainties from the corrected data plotted as a function of latitude in 5° wide bins. As expected for Poisson statistics, the uncertainties are the lowest at the poles and greatest near the equator.

3.2 Systematic uncertainties due to background variations

We investigate systematic uncertainties due to non-uniform background variations [i.e. the breakdown of assumption (1)] using orbital, calibration, and model derived γ -ray spectra. Figure 3 shows orbital γ -ray spectra (2 – 3 MeV) for three different $30^\circ \times 30^\circ$ regions centered about the lunar equator. Region 1 ($-30^\circ < \text{longitude} < 0^\circ$) is a high thorium region ($6.4 \mu\text{g/g}$), region 2 ($15^\circ < \text{longitude} < 45^\circ$) is a moderately high thorium region ($1.9 \mu\text{g/g}$), and region 3 ($120^\circ < \text{longitude} < 150^\circ$) is a low thorium region ($0.9 \mu\text{g/g}$). If we invoke assumption (2) (i.e. assume that the low thorium region has little or no thorium), then the region 3 spectrum is an approximate background spectrum for the energy window containing the thorium line.

Figure 4 shows spectra from regions 1 and 2 after the background spectrum (region 3) has been subtracted. Also shown are calibration and model derived spectra that have been scaled to the orbital spectra. The calibration spectrum was taken with the GRS before launch and contains an uncalibrated 2.61 MeV thorium line from the naturally occurring thorium in the concrete floor and walls of the laboratory. The model spectrum was calculated using a Monte Carlo simulation of the GRS detector response [Lawrence *et al.*, 1999a, Prettyman *et al.*, 1998]. As seen, the fit is generally better for all three spectra between the energies 2.5 – 2.7 MeV than for the 2.4 – 2.8 MeV window which was used previously in Lawrence *et al.* [1998] to derive relative thorium abundances. Specifically for the 2.4 – 2.8 MeV window, the orbital data clearly show excess counts relative to both the calibration and model spectra.

To estimate the possible magnitude of systematic uncertainties due to non-uniform background counts, a series of calculations has been carried out with the global 60 km x 60 km data. The total number of counts above background have been calculated for a number of different window widths ($\Delta E = 0.05 - 0.4$ MeV) centered about 2.61 MeV. These measured counts were normalized to the detector efficiency using the calculated model spectrum. The counts from each window width, $C_{\Delta E}$, were then compared to the counts, $C_{0.2}$, calculated using the nominal window width of 0.2 MeV. Figure 5 shows the results of these calculations where the window width is plotted versus the globally averaged ratio $\langle (C_{\Delta E} - C_{0.2})/C_{0.2} \rangle$. The error bars are the calculated standard deviation of the global average. If abundance variations from the 2.61 MeV thorium line are the only source of global variations for the counts within these window widths, then the ratio $\langle (C_{\Delta E} - C_{0.2})/C_{0.2} \rangle$ should be 0.

Figure 5, however, shows that as the window width increases, more counts are measured than can be accounted for by just scaling the detector efficiency. It is likely that many of the excess counts for the larger window widths result from γ -ray lines from elements other than thorium that have energies near 2.61 MeV but have fluxes and variability substantially lower than the thorium γ -rays. These elements include silicon and oxygen, which likely have little variation over the Moon, as well as iron, magnesium, aluminum, which might have larger compositional variations (see *Reedy* [1978] for a listing of γ -ray lines). In particular, we notice that the high-altitude data show a greater variability from the nominal window width than the low-altitude data. This effect may result from incomplete corrections for systematic uncertainties (see Figure 1a). In addition, the high-altitude data average over much larger areas than the low-altitude data [(150 km)² versus (45 km)²]. As there are numerous regions on the Moon which are compositionally inhomogeneous over these spatial scales, these inhomogenities may manifest themselves with greater variations in the high-altitude data.

As the window width narrows, the trend is less clear. In this case, it is possible that in addition to a non-uniform background, the peak parameters of the model spectrum used to calculate efficiencies does not exactly match the peak parameters from the orbital data. In addition, the number of counts used to make the measurement becomes quite small and Poisson variations start to become important which may be contributing to the

larger error bars. Yet in spite of these details, the variations given by Figure 5 likely represent the upper limit of any non-uniform background variations that are also present in the measured abundances. Using Figure 5 as a guide, we estimate that the relative systematic errors due to non-uniform background variations are no greater than 30% (high-altitude) and 15% (low-altitude) and no less than 10% (high-altitude) and 4% (low-altitude).

3.3 Summary of abundance uncertainties

From the preceding discussion, we conclude that systematic uncertainties from non-uniform background variations is the dominant uncertainty for most abundances measurements. For example, with the low-altitude data, the abundance measurements in all pixels have an upper limit on their relative systematic uncertainties of (+4%, -15%). However, for abundances less than 2 $\mu\text{g/g}$ at low latitudes (see Figure 2), uncertainties due to Poisson statistics and time dependent corrections start to be important. As the estimates of thorium abundances are improved with more detailed spectral analyses, we expect the final uncertainties to be close to lower physical limit determined by Poisson statistics.

4. Global thorium abundances

4.1 High-altitude versus low-altitude data

Thorium abundance maps for both the high- and low-altitude data are shown in Plate 1. These global maps show the derived thorium abundances overlaid with a lunar surface features map. We see the same thorium surface features that were identified in earlier studies, but now we are able to make a comparison between the two data sets. From these maps, it is clear that the low-altitude data have distinctly better surface resolution than the high-altitude data. In particular, many of the high thorium regions that appear to be contiguous in Plate 1a are resolved into distinct regions in Plate 1b. A clear example of the better resolution of the low-altitude data set is seen with the identification of the Compton/Belkovich thorium-rich region (60°N, 100°E) first reported in *Lawrence et al.* [1999a]. The size of this region is approximately 150 – 300 km diameter which is similar to the (150 km)² surface resolution of the high-altitude data set.

The two data sets are compared directly in Figure 6 which is a scatter plot of the derived thorium abundances for the two data sets. In Figure 6, the small points are the global data, the solid line is the unity line, and the large circles (both in the top and bottom panels) show the average low-altitude abundance within 0.5 $\mu\text{g/g}$ high-altitude abundance bins. For abundances greater than 6 $\mu\text{g/g}$, we see that the low-altitude derived abundances are consistently higher than the high-altitude derived abundances. If this effect is not due to systematic uncertainties (the uncertainties discussed in Section 3.2 were upper limits and may be smaller), this observation suggests that the majority of regions with abundances greater than 6 $\mu\text{g/g}$ have small areas of less than $(150 \text{ km})^2$ (the surface resolution of the high-altitude data). This is a reasonable interpretation because the high-altitude measurements smooth and average data over an area of $(150 \text{ km})^2$. Small area, high-thorium regions will therefore appear to have lower thorium abundances in the high-altitude measurements compared to the low-altitude measurements. It is also possible that some or all of these regions have areas which still lie unresolved in the low-altitude data set. If such regions exist, it's possible they may be identified with subsets of the low-altitude data. As seen in Table 1, 10% of the low-altitude data were taken from heights of less than 20 km so for this data subset, the surface resolution would be correspondingly better.

In contrast to the high-thorium regions, Figure 6 shows that for thorium abundances less than 6 $\mu\text{g/g}$, there is a one-to-one correspondence between the two data sets. This implies that the majority of regions with thorium abundances less than 6 $\mu\text{g/g}$ have thorium surface distributions that are homogeneous on the scale of an area greater than $(150 \text{ km})^2$. However, as demonstrated by the Compton/Belkovich thorium anomaly (see Plate 3a and *Lawrence et al.*, [1999a]), not all regions with measured thorium abundances less than 6 $\mu\text{g/g}$ are homogeneous on a scale of $(150 \text{ km})^2$.

4.2 Thorium abundances versus topography

A comparison of thorium abundances with topography is shown in Figure 7 where the topographic data of *Smith et al.* [1997] have been smoothed to the footprint of the GRS data using an equal area Gaussian smoothing algorithm. From Figure 7, it appears that the surface thorium abundances are segregated by topography into two components.

For low thorium abundances, there is a general inverse correlation between topography and thorium. The lowest thorium abundances are seen at the highest elevations while relatively higher thorium abundances are seen at the lowest elevations. This relationship was identified by *Trombka et al.* [1973] and *Metzger et al.* [1977] for the lunar equatorial regions using Apollo GRS data. With the LP data, we see that this inverse relationship continues to hold for most of the lunar highlands. The existence of this low-thorium component, located mostly in the highlands and in SPA basin (see below), suggests that the process which emplaced the thorium is global in nature. This relationship of increasing thorium for lower elevation is exactly what is expected if increasing amounts of lower crustal material is being exposed from greater depths [*Ryder and Wood*, 1977; *Ryder and Spudis*, 1987]. In particular, this thorium/topographic relationship appears to be signature of the global differentiation of the Moon [*Vaniman et al.*, 1991].

In light of these data, the thorium deposition model of *Haskin* [1998] may need to be studied in greater detail. In his model, Haskin proposes that most if not all the highlands thorium was globally deposited by the Imbrium impact. While there is evidence for such deposition (see Figure 5 of *Lawrence et al.*, [1998]), the Haskin model needs to be understood within the context of the topographic/highlands thorium relationship seen in Figure 7.

In contrast to the inverse topography/thorium relationship seen in the highlands, the high-thorium regions which exist on the nearside show very little if any correlation with topography. This observation suggests that the nearside thorium was emplaced by a fundamentally different process than most of the farside highlands thorium. However, one location that might show a slight positive correlation with topography is the region surrounding Fra Mauro which contains some of the largest observed thorium abundances seen on the Moon (open circles and inset). The Fra Mauro data of Figure 7 were selected to show all of the pixels within the region of (15°S – 20°N, 45°W – 0°) having thorium abundances greater than 6 µg/g. This selection defines a high-thorium region which roughly extends from the Carpathian Mountains at (15°N, 30°W) to Lalande crater at (4°S, 9°W). The inset shows the mean topography (solid circles) and 25th and 75th percentiles (lines) for 0.5 µg/g thorium abundance bins.

This observation is important because there has been much controversy regarding the nature of the high-thorium material in the Fra Mauro region. Some investigators suggest that most of the material within the Fra Mauro region consists of primary Imbrium ejecta [*Wilhelms*, 1987 and references therein] while others maintain that most of the material within Fra Mauro is derived from secondary ejecta and/or KREEP volcanism [*Hawke and Head*, 1978 and references therein]. The slight positive topography/thorium correlation seen with the LP data is not consistent with the analysis of *Hawke and Head* [1978] where an inverse topography/thorium relation was identified for areas around Fra Mauro using Apollo GRS data. Specifically, *Hawke and Head* showed that for a region extending from Ptolemaeus to Fra Mauro to Mare Cognitum, the thorium abundances increased for lower depths. This observation was interpreted as evidence that the high-thorium material in Fra Mauro was possibly deposited by KREEP volcanism. However, with the new LP data, it seems more appropriate to study the topographic/thorium relationship in the Fra Mauro region using the high-thorium region that is clearly defined by the data (as described above). This region likely represents a more distinct terrain than the highland/mare boundary studied by *Hawke and Head*. With this new region, the inverse relation of *Hawke and Head* is certainly no longer seen and there may even be a slight positive correlation. Detailed studies of this region using additional information such as the geologic maps of *Wilhelms* [1987] and remotely sensed iron and titanium abundance data from Clementine and Lunar Prospector will certainly provide more understanding of the nature of the topography/thorium relationship in the Fra Mauro region.

5. Regional Thorium Abundances

In this section, we investigate a number of regions using the low-altitude thorium data. Some of these regions have been places of interest for a long time (SPA basin, Tycho crater) and others have been identified as thorium anomalies for the first time using the LP data (Compton/Belkovich, western Tranquillitatis).

5.1 South Pole Aitken Basin

The South Pole Aitken (SPA) basin is special since it is the largest impact basin on the Moon with a depth of 12 km and diameter of 2500 km [*Spudis et al.*, 1994]. Because of its great size, the impact which created this basin excavated material deep from the lunar crust and maybe even from the mantle. In fact, recent studies using data from Clementine have shown that SPA basin is a distinct region containing compositions thought to be derived from either the lower crust [*Pieters et al.* 1997] or a combination of mantle and lower crustal material [*Lucey et al.* 1998].

The thorium abundances within SPA have been briefly described in previous studies [*Lawrence et al.*, 1998, 1999a], but this is the first time that low-altitude thorium data have been shown in detail for SPA basin. Plate 2 shows three different views of SPA basin. Plate 2a shows the low-altitude thorium abundances, Plate 2b shows FeO abundances derived from Clementine Spectral Reflectance (CSR) data by *Lucey et al.* [2000], and Plate 2c shows topography data given by *Smith et al.* [1997]. The thorium within SPA appears to segregate into two components: a low abundance, diffuse component and a moderately high abundance, localized component.

The low abundance component has an average concentration of 1.5 – 3 $\mu\text{g/g}$ and is distributed over the entire basin as delineated by both FeO and topography data. With some exceptions, the low abundance component appears to follow the general trend with topography that is seen for the highlands thorium abundances (see Figure 7). Specifically, the deepest part of SPA is in the southern portion and this is also where the highest thorium abundances of the low abundance component are located. One notable exception to this trend is found at Apollo basin (36°S, 152°W). Portions of Apollo basin extend to more than 5 km below the mean lunar radius and the thorium abundances in this region are distinctively low compared to the surrounding regions. However, as seen in the FeO data and in the geologic maps of *Wilhelms* [1987], these locations within Apollo are filled with high-FeO mare basalt. Another location which does not appear to follow the highlands topography/thorium relationship is at the three craters Minnaert (68°S, 180°), Antoniadi (70°S, 172°W), and Numerov (71°S, 161°W). While all three craters show up in Plate 2c as topographic lows, the middle crater, Antoniadi, appears to show relatively less thorium than its two neighbors. According to *Wilhelms*, Antoniadi is the only crater of this trio which also has mare basalt fill. Other locations having high

FeO mare basalts while also containing relatively low thorium abundances include Leibnitz (38°S, 179°E), Poincare (57°S, 164°E), and Mare Ingenii (34°S, 164°E). This observation that mare basalts within SPA basin may contain relatively low thorium abundances is contrary to what was described by *Hawke and Spudis* [1980] using Apollo GRS data. However, since the uncertainties of these low abundance data may be large, this mare basalt/thorium relation needs to be confirmed with more detailed regional studies and data analysis.

In contrast to the large area, low abundance component, the moderately high abundance component is concentrated in the northwest portion of SPA basin with two abundance maxima centered near Birkeland crater (30°S, 173°E) and an unnamed crater (41°S, 165°E) between the craters Obruchev (39°S, 162°E) and Oresme (42°S, 169°E). However, it does not appear that the high-thorium component is directly associated with these craters. The entire high-thorium component extends roughly from (22°S, 180°) to (50°S, 160°E). One reason we consider this region to be a different thorium component is that it does not follow the highlands topographic/thorium relationship of Figure 7. In fact, the highest elevations inside SPA are at the same place where we see this high abundance component. We also note that the outlines of this component do not appear to be correlated with the optically derived FeO and TiO₂ (*Lucey et al.*, [2000] not shown) abundances.

When these observations are connected with the topography/thorium relationship of Figure 7, we conclude that the low abundance component seen in SPA basin is likely part of the global highlands thorium component in which higher thorium, lower crustal material is being exposed. This interpretation is consistent with the *Lucey et al.* [1998] explanation that much of the material within SPA basin has a one-to-one composition of mantle and lower crustal material.

In contrast, the high abundance component does not follow the highlands topographic/thorium relationship and does not appear to be correlated with the optically estimated FeO and TiO₂ abundances. We therefore suggest that this component was emplaced by a process that is fundamentally different than the process which emplaced the low abundance component. One possible explanation for the existence of the high abundance component is that this thorium is associated with ancient mare basalt deposits

that were covered over as a result of extensive mass wasting caused by seismic waves from the Imbrium impact event [Hawke and Spudis, 1980]. However, as was described earlier, we see indications of an anti-correlation of thorium with exposed mare basalt, not a correlation. If the ancient mare basalt units described by Hawke and Spudis are similar to the exposed mare basalts, then ancient mare basalts would not be the source of the high thorium abundances. There are other reasons such a scenario appears unlikely. The layer covering these ancient mare deposits would have to either be very thin ($\sim 30 \text{ g/cm}^2$, see Evans *et al.* [1993]) so that the thorium γ -rays could penetrate the layer, and/or there would have to be a very high density of high-Th dark halo craters over very large areas (the southern portion of the high abundance component has an area of roughly $240 \times 360 \text{ km}$). Since $10 - 100 \text{ cm}$ of lunar soil is reworked every 10^9 years [McKay *et al.* 1991; Langevin and Arnold, 1977], a covering of $<30 \text{ g/cm}^2$ would probably not survive the $3 - 4 \times 10^9$ years since the Imbrium impact. It is also unlikely that there exists a density of dark halo craters large enough to create the large thorium signal we see over such large areas. For example, Blewett *et al.* [1999] identified an unnamed dark halo crater (39°S , 157°E) as having high FeO and TiO_2 abundances. This crater, however, is not located within the region containing the highest thorium abundances. If other dark halo craters behave similarly, it is therefore unlikely that covered over basalt deposits are the source of the high-Th regions.

Another possible explanation for the existence of the high-thorium component is that it might be ejecta from the Imbrium impact as suggested by Haskin, [1998], and Haskin *et al.*, 1998] because it is located very close to the antipode of Imbrium basin. While intriguing, these data need to be investigated in more detail and compared with other data sets before such a conclusion is shown to be compelling.

5.2 Compton/Belkovich thorium anomaly in the northern highlands

Most of the lunar highland regions have low thorium abundances of less than $2 \mu\text{g/g}$. However, one location of anomalously high thorium abundances is the Compton/Belkovich region in the northeastern highlands [Lawrence *et al.*, 1999a]. This anomalous high-Th region (Plate 3a) is located at (60°N , 100°E) between the craters Compton (55°N , 105°E) and Belkovich (63°N , 90°E). The measured thorium

abundances range from 2 – 4 $\mu\text{g/g}$ over an area of 150 – 300 km^2 . While not shown, an investigation of raw γ -ray spectra shows that this region also has anomalously high potassium abundances. The potassium abundance, however, cannot be quantified until the full spectral deconvolution analysis is carried out with the GRS data. Because the GRS measures thorium abundances averaged over large areas, it is not clear from these data whether this high-thorium anomaly has a small size [$<(45 \text{ km})^2$] with high thorium abundance ($> 4 \mu\text{g/g}$), or if it is $\sim(150 \text{ km})^2$ in size with a moderately high thorium abundance (2 – 4 $\mu\text{g/g}$). The optically derived FeO abundances in this region (Plate 3b, *Lucey et al.*, 2000] show no anomalous features for the location of the high-thorium anomaly. The FeO abundances look very much like normal highlands material with values in the broad range of 0 – 6 wt.%. TiO_2 measurements from Clementine (not shown) also indicate very low abundance values. In a complementary analysis carried out by *Thomsen et al.* [1999], it is further found that no other location on the Moon has such high thorium abundances coincident with such low FeO and TiO_2 abundances, i.e. this location is compositionally unique on the Moon. Finally, the topography in this region (Plate 3c, *Smith et al.* [1997]) shows a relative depression almost coincident with the location of the high-thorium anomaly. We currently do not understand how this topographic depression relates to the thorium anomaly.

From the composition data, it appears that we are identifying a concentration of highly evolved material in the Compton/Belkovich region. Specifically, the high thorium and low iron and titanium abundances suggest that this region may contain high concentrations of either alkali anorthosite and/or granite. *Korotev* [1998] has compiled elemental abundances (Al, Ti, Fe, K, Th, and U) for a number of different types of highly evolved igneous rocks. *Taylor et al.* [1991] and references therein also list measured bulk compositions for evolved lunar samples. The average thorium abundance for ten different granites and/or felsites is $36 \pm 13 \mu\text{g/g}$ [*Korotev*, 1998]. In contrast, the average thorium abundance for alkali anorthosites is $4.8 \pm 3.3 \mu\text{g/g}$. If the Compton/Belkovich anomaly is indeed dominated by granite, then it must be a small area with very high thorium abundances. We can test for the presence of granite by looking at potassium, silicon, and possibly iron abundances. The potassium to thorium ratio for granite should be over 50% greater (970 versus 416, see Figure 1 of *Korotev* [1998]) than would be

expected for a rock having KREEP-type ratios. As previously mentioned, we do see an anomalously high potassium abundance in the raw count rate data, but the raw potassium counts do not deviate significantly from the constant potassium to thorium count rate ratio that is seen over the whole Moon [Lawrence *et al.*, 1998]. However, since the potassium abundance has not been quantified with the spectral deconvolution analysis, we cannot conclusively determine if the potassium abundance is larger than would be expected for normal KREEP ratios. Regarding silicon abundances, Taylor *et al.* [1991] and Haskin and Warren [1991] show that SiO₂ abundances should be over 30% larger for granite compared to most other lunar rock types (73 wt.% versus 40 – 50 wt.%). While the strongest silicon γ -ray line at 1.78 MeV should be sensitive to such an abundance difference, a determination of the relative silicon abundance has not yet been carried out because there are a number of thorium and uranium lines that interfere with the silicon line. Finally, iron abundance measurements might help to discriminate what type of material dominates this anomalous region. According to Korotev [1998], the average FeO abundance of granite and felsite is 7.7 ± 3.9 wt.% and the average alkali anorthosite abundance is 2.8 ± 1.0 wt.%. A close inspection of the $0.25^\circ \times 0.25^\circ$ FeO map by Lucey *et al.*, [2000] shows a noisy salt and pepper distribution with FeO abundances generally ranging from 4 – 5 wt.% in the eastern part of the anomaly to 1 – 2 wt.% in the western part of the anomaly. If the Clementine derived FeO abundances do represent the true iron abundances and the potassium abundances are present in KREEP-like ratios, then these data suggest that the dominant lithology in this region is more like an alkali anorthosite than a granite.

5.3 Other regions of interest

We have identified an isolated high thorium concentration within the western portion of Mare Tranquillitatis. Plate 4 shows a map of thorium abundances for the western Tranquillitatis region. As seen, the high thorium concentration is centered on the crater Arago, a 26 km diameter crater located at (6.2°N , 21.4°E). The measured thorium abundance around Arago is between 3.6 and 5.4 $\mu\text{g/g}$ and shows an asymmetric thorium distribution where the higher thorium abundances are located to the west of Arago. We also note that highland material excavated from beneath the mare by Arago was mapped

using Clementine data by *Staid et al.*, [1996]. *Staid et al.* showed that the larger crater Plinius (15.4°N, 23.7°E) also excavated highland material from beneath the mare, but Plate 4 shows that it does not exhibit a high-thorium anomaly. The existence of this high thorium anomaly at Arago crater is therefore interesting because it shows there was at least some high thorium regions not directly located beneath the Imbrium/Procellarum and is evidence for some degree of thorium inhomogeneity at depth on the lunar nearside.

The last region we describe here is Tycho crater (43°S, 11°W). In contrast to the high thorium abundances seen elsewhere, Tycho shows some of the lowest thorium abundances seen on the entire Moon. Plate 5 shows a map of thorium abundances and Clementine albedo data [*Robinson et al.*, 1999] in the region around Tycho. Plate 5a shows that the area around Tycho has very low thorium abundances with the lowest abundances located directly over Tycho. We also note that low thorium abundances appear to overly much of the Tycho's ray structure, particularly the ray structure northeast of Tycho.

As explained by *Pieters* [1986, 1993], the areas in and around Tycho appear to be enriched by a gabbroic high-calcium pyroxene which is thought to be plutonic in nature. In regards to KREEP abundances of plutonic rocks, *Korotev* [1998] predicted that while some rocks from the Apollo 15 and 17 collections such as norite and troctolite (and by extension gabbro) may have assimilated a KREEP component during their formation, such plutonic rocks that occur away from Imbrium basin (where the large KREEP abundances are found) may have substantially lower concentrations of radioactive elements. This is indeed just what is seen with the thorium data at Tycho. If the gabbroic material identified by *Pieters* represents an excavated plutonic structure, then this material did not assimilate KREEP which suggests that KREEP was absent at depth from at least this portion of the Moon.

6. Summary

In this paper, we have presented an overview of the lunar thorium abundances and uncertainties that have been measured using the Lunar Prospector Gamma-Ray Spectrometer. Specifically, we have shown that the measured uncertainties for both the high- and low-altitude are less than 0.5 µg/g. Other systematic uncertainties may be

somewhat larger, but with future analysis, we expect to be able to reduce significantly the uncertainties from variations in background counts.

Comparisons of the high- and low-altitude thorium abundance data show a very good correspondence especially for thorium abundances less than 6 $\mu\text{g/g}$. Because of the smaller spatial resolution of the low-altitude data, we see evidence that a significant portion of the regions with thorium abundances greater than 6 $\mu\text{g/g}$ may likely be small area regions $\leq (150 \text{ km})^2$. From the low-altitude data, we see that some of these small area, high-thorium regions are directly related to craters on the nearside. While most of these craters are located around the rim of Imbrium basin [Lawrence *et al.*, 1999a], we have identified at least one high-thorium crater (Arago) in western Tranquillitatis not directly associated with Imbrium basin.

As delineated by topography, it appears that thorium has been globally emplaced by at least two different processes. For the highlands regions and much of SPA, the low to moderate thorium abundance is inversely correlated with topography. This is the signature one expects if the Moon underwent a global differentiation process with more mafic and thorium rich materials increasing in abundance at lower depths. While there is evidence to show that thorium in the highlands may have been globally emplaced by the Imbrium impact [Haskin, 1998, Lawrence *et al.*, 1998], this interpretation needs to be reconciled with the topographic/thorium relationship we observe here.

Exceptions to the global topographic/thorium distribution have been identified in a number of locations. The highest thorium region in SPA is located not in a topographic low, but at the highest elevations within SPA. This suggests that the thorium in this location was emplaced by a process different from which emplaced much of the thorium elsewhere in SPA and the highlands. The Compton/Belkovich high thorium anomaly, while located in a topographic low point, shows no mafic anomalies. This suggests that this region may be enriched with evolved lithologies and to date represents the only such extended region on the Moon that has been identified. Finally, the low thorium abundances at Tycho crater, which is thought to be an excavated plutonic complex, demonstrate that thorium (and by extension KREEP) was not assimilated at depth in this portion of the Moon.

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Figure Captions

Figure 1: Scatter plot of Poisson uncertainties versus measured uncertainties for high-altitude (Figure 1a) and low-altitude (Figure 1b) data. The black circles show the data before time dependent corrections (i.e. corrections for gain variations, cosmic ray variations, etc.) have been made. The gray crosses show the data after these corrections have been made. The solid black line is the unity line for which Poisson uncertainties equal the measured uncertainties.

Figure 2: Measured uncertainties for the corrected data versus latitude. The solid heavy line shows the mean uncertainty for 5° wide latitude bins and the vertical lines show the 25th and 75th percentile values for the 5° wide latitude bins.

Figure 3: Orbital γ -ray spectra of three different $30^\circ \times 30^\circ$ regions on the Moon from the high-altitude (Figure 3a) and low-altitude (Figure 3b) data. Region 1 ($15^\circ\text{S} - 15^\circ\text{N}$, $30^\circ\text{W} - 0^\circ$) has high thorium concentrations, region 2 ($15^\circ\text{S} - 15^\circ\text{N}$, $15^\circ\text{E} - 45^\circ\text{E}$) has medium high thorium concentrations, and region 3 ($15^\circ\text{S} - 15^\circ\text{N}$, $120^\circ\text{E} - 150^\circ\text{E}$) has low thorium concentrations.

Figure 4: Background subtracted γ -ray spectra for regions 1 and 2. High-altitude data are shown in Figures 4a – 4b and low-altitude data are shown in Figures 4c – 4d. Also shown are the laboratory calibration and model derived spectra which have been scaled to the measured orbital spectra. The 2.6 MeV thorium peak is clearly seen in all spectra. The peak at 2.1 MeV in the model spectrum is the first escape peak from the 2.6 MeV thorium line. In the laboratory and orbital spectra, this peak appears shifted because there likely is a 2.2 MeV line from uranium in the laboratory data and 2.2 MeV lines from uranium and aluminum in the orbital data superimposed on the 2.1 MeV thorium escape peak.

Figure 5: Global average of the value $(C_{\Delta E} - C_{0.2})/C_{0.2}$ versus the selected window width around the 2.61 MeV γ -ray line for high-altitude data (solid circles) and low-altitude data

(open squares). The error bars are the measured standard deviations of the global average. The vertical line is the full-width, half maximum of the model and calibration peak (0.187 MeV).

Plate 1: Global maps of measured thorium abundances for high-altitude data (Plate 1a) and low-altitude data (Plate 1b).

Figure 6: Scatter plot of measured thorium abundances for high and low-altitude data (Figure 6a). The small circles show the measured abundances for each $2^\circ \times 2^\circ$ pixel, the solid line is the unity line, and the large filled circles shows the median low-altitude abundance value for 0.4 $\mu\text{g/g}$ wide bins of high-altitude abundances. The bottom panel (Figure 6b) show the residual low-altitude abundance that lies either above or below the unity line for each of the 0.4 $\mu\text{g/g}$ high-altitude abundance bins.

Figure 7: Measured thorium abundances versus topography measurements smoothed to the footprint of the high-altitude (Figure 7a) and low-altitude (Figure 7b) data. The inset in each plot shows the mean topography (solid circles) and 25th and 75th percentile values (vertical lines) within 0.5 $\mu\text{g/g}$ wide thorium abundance bins for the Fra Mauro region as described in the text.

Plate 2: South Pole Aitken basin as seen with three different data sets (color coded) overlaid with a lunar surface features map. Plate 2a shows thorium abundances from the low-altitude data set, Plate 2b shows optically derived FeO abundances from *Lucey et al.*, [2000], and Plate 2c shows topographic data taken from *Smith et al.*, [1997]. The brown color indicates that either the data are offscale or not available.

Plate 3: North pole region as seen with three different data sets (color coded) overlaid with a lunar surface features map. Plate 3a shows thorium abundances from the low-altitude data set, Plate 3b shows optically derived FeO abundances from *Lucey et al.*, [2000], and Plate 3c shows topographic data taken from *Smith et al.*, [1997]. The

Compton/Belkovich thorium anomaly is located at (60°N, 100°E). The brown color indicates that either the data are offscale or not available.

Plate 4: Thorium abundances overlaid with a lunar surface features map seen for the western Tranquillitatis region. The brown color indicates that either the data are offscale or not available.

Plate 5: Tycho crater as seen with two different data sets (color coded) overlaid with a lunar surface features map. Plate 5a shows thorium abundances from the low-altitude data set and Plate 5b shows albedo data taken from *Robinson et al.*, [1999].

	High-altitude data set	Low-altitude data set
Dates	16 Jan. 1998 – 19 Dec. 1998	19 Dec. 1998 – 22 May 1999
Type	high-altitude, spin axis north and south	low-altitude, spin axis south
Mean height	99.8 km	32.3 km
10th and 90th height percentiles	88.5/111.2	20.9/43.8 km
Number of 32- second spectra	787,096	517,378
spectra per 60x60 km pixel for $\lambda = \pm 90^\circ, \pm 45^\circ, 0^\circ$	2500, 62, 50	1600, 41, 34
Percentage of possible spectra	86.3%	86.9 %

Table 1: Mean height and number of spectra collected for the high- and low-altitude data sets.